Future galactic supernova neutrino signal: What can we learn? *

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Abstract

The next supernova in our galaxy will be detected by a variety of neutrino detectors. In this lecture I discuss the set of observables needed to constrain the models of supernova neutrino emission. They are the flux normalizations, and average energies, of each of the three expected components of the neutrino flux: ν_e, $\bar{\nu}_e$, and ν_x (all the other four flavors combined). I show how the existing, or soon to be operational, neutrino detectors will be able to determine the magnitude of these observables, and estimate the corresponding rates.

1 Introduction

When neutrinos from supernova 1987A were detected by the Kamiokande [1] and IMB [2] collaborations, a new era of neutrino astrophysics began. Despite the limited statistics (11 events in Kamiokande and 8 events in IMB) the observation confirmed that the core collapse supernovae emit most of their binding energy (a few$\times 10^{53}$ erg) in neutrinos, that the duration of the neutrino emission is ~ 10 seconds, and that the average energy of the neutrinos (at least of the $\bar{\nu}_e$, which were the only flavor actually seen) is ~ 15 MeV, close to expectations. The observation of SN1987A lead to a flood of papers analyzing its consequences (for a relatively early review, see e.g. [3]), which is only very slowly diminishing with time.

Historically, there were seven supernovae in our galaxy proper recorded in the past thousand years, and none in the last three centuries (some were not core-collapse SN which emit neutrinos, though). All of them were relatively close to the solar system, so it is difficult to estimate the true rate averaged over the whole galaxy from this record. Consensus estimate of core-collapse supernova rate in our galaxy is about three times per century [4]. Thus, the next Galactic supernova neutrino burst can come at any time, tomorrow or in several decades. It is likely that neutrinos from such supernova will be detected by a variety of detectors, with much better statistics than for SN1987A. Thus a wealth of new information is expected from such unique event which cannot be repeated in the productive lifetime of an average physicist. (Unfortunately, the present or planned neutrino detectors are unable to observe supernovae in even the nearest galaxy, Andromeda, about 700 kpc away.) Here I discuss some of the lessons that should, and hopefully will, be extracted from the neutrino signal of the next supernova in our galaxy.

There are several areas of physics that will greatly benefit from the supernova neutrino observations. They can be divided into three broad categories:

1.) Neutrino properties; mass, mixing, decay, etc. In particular, one could use the time-of-flight of the neutral current signal (dominantly ν_μ and ν_τ) to reach sensitivity to masses of about 30 eV

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for these neutrinos [5, 6]. This would represent an improvement by more than three orders of magnitude for the mass associated with ν_μ, and by almost six orders of magnitude for the mass associated with ν_τ when compared to the present direct neutrino mass limits [7]. If, moreover, the neutrino emission is abruptly truncated by the collapse of the proto-neutron star into a black hole, one can use this sharp cut-off in the neutrino signal to improve the time-of-flight sensitivity to masses of $\sim$ 6 eV for ν_μ and ν_τ and to $\sim$1.8 eV for ν_e [8].

2.) Supernova properties. From the neutrino signal it might be possible to determine the luminosities and average energies of all three components of the neutrino flux: ν_e, $\bar{\nu}_e$, and ν_x (this notation will be used from now on collectively for ν_μ, ν_τ and their antiparticles).

3.) Supernova localization. Using the angular distribution of the products of the neutrino induced signal, or the timing of the signal recorded in widely separated detectors, it might be possible to find the direction towards the supernova independently, or prior to, of the optical signal (for the discussion of this item, see [9]).

I refer to the listed references regarding the items 1.) and 3.) and in the following I will concentrate on the item 2.) - the determination of supernova properties from the neutrino signal. My aim is going to be a definition of a 'template', i.e., a recipe how to determine the required quantities and what signal and statistical accuracy one may expect using the existing, or soon to be operational, detectors. Substantial deviations from this template will mean either that the supernova behaves in an unexpected way, or that neutrino oscillations affect the signal. Obviously, general analysis of all possibilities is impossible before the fact. However, the existence of such a template might help in preparing the detectors for the supernova signal, particularly those like SuperKamiokande, SNO, KamLAND or Borexino, which are built for a different purpose.

I will consider a 'standard' supernova (for a review of Type-II supernova theory see [10]), approximately at the center of the galaxy, at the distance from Earth of 10 kpc. The binding energy, which is essentially fully emitted in neutrinos, is assumed to be 3×10^{53} ergs. It is easy to understand the magnitude of the binding energy E_B by using the simple estimate

$$E_B \simeq \frac{3}{5}\frac{G_N M^2}{R}, \quad \text{where } R = 10 \text{ km}, \quad M \simeq 1.4 M_\odot \ . \tag{1}$$

Neutrinos are trapped in the hot and dense protoneutron star. The mean free path of neutrinos,

$$\lambda = \frac{1}{\rho\sigma} \sim 10 \text{ m for } \rho \sim 10^{38} \text{ nucleons/cm}^3 \ , \ \sigma \sim 10^{-41} \text{ cm}^2 \tag{2}$$

is substantially shorter than the radius of the protoneutron star. In fact, the trapping occurs already when the star radius is $\sim$ 100 km and the mean free path becomes comparable to the scale height h of the infalling matter ($h = kT/M_p g$ where $g \sim 10^{12}$ ms^{-2} is the gravitational acceleration at that radius).

Trapped neutrinos diffuse through the protoneutron star. They leave the star when they reach the so-called neutrinosphere, essentially the radius where their mean free path is comparable to the corresponding scale height at that point. Again, a crude estimate of the diffusion time is just the product of the time duration between successive scatterings and the number of steps,

$$\tau_{diff} \sim \frac{\lambda}{c}\frac{R^2}{\lambda^2} \ \sim \ 10 \text{ s} \ . \tag{3}$$

Throughout the star, neutrinos of all flavors are in equilibrium, with decreasing temperature at increasing radii. Thus, the temperature of the outgoing neutrino flux for each flavor will be the characteristic temperature of the corresponding neutrinosphere. Since the mean free paths of the different neutrino flavors are different, the position of their neutrinospheres, and hence also the decoupling temperatures, will be different as well. The ν_x neutrinos undergo only neutral current interactions, hence their mean free path is longest, and thus their decoupling temperature will be highest. Both ν_e and $\bar{\nu}_e$ have in addition also charged current interactions. Moreover, since the star contains many more neutrons than protons, the ν_e mean free path will be shorter (since ν_e interact with neutrons) than the $\bar{\nu}_e$ mean free path (since $\bar{\nu}_e$ interact with protons). Hence a hierarchy of decoupling temperatures (or mean energies) is expected,

$$T(\nu_x)(\sim 8\text{MeV}) > T(\bar{\nu}_e)(\sim 5\text{MeV}) > T(\nu_e)(\sim 3.5\text{MeV}) \ , \tag{4}$$

or

$$\langle E_{\nu_x} \rangle \sim 25 \text{ MeV} > \langle E_{\bar{\nu}_e} \rangle \sim 16 \text{ MeV} > \langle E_{\nu_e} \rangle \sim 11 \text{ MeV} \ . \tag{5}$$

At the same time, one expects that the total luminosity will be equally shared by all neutrino flavors, so averaged over time

$$\langle L_\nu \rangle \simeq \frac{E_B}{6\tau_{diff}} \simeq 5 \times 10^{51} \text{ erg/s} \ \text{ for all 6 flavors} \ . \tag{6}$$

Note that the the short initial ν_e neutronization pulse has only small luminosity when compared to $\langle L_\nu \rangle$ and is going to be difficult to observe. For a detailed description of the supernova neutrino emission, including the justification of the choice of the decoupling temperatures, see Refs. [11, 12].

For each neutrino flavor the corresponding time averaged flux at Earth will be therefore

$$\langle f_\nu \rangle = \frac{2.6 \times 10^{11}}{\langle E_\nu \rangle (\text{MeV})} \text{ cm}^{-2} \text{ s}^{-1} \ , \tag{7}$$

for the assumed 10 seconds emission time. With such a flux and a typical cross section of $\sim 10^{-41}$ cm^2, one expects few hundred charged current interactions with protons in 1 kton of water, and few tens of events in 1 kton of iron (or other heavy target). Clearly, very large detectors, operating for a long time, are needed.

Thus the challenge for supernova neutrino observers is to detect separately the three expected components of the neutrino flux: the ν_e component through the charged reaction on bound neutrons (i.e., on nuclei), the $\bar{\nu}_e$ component most easily through the charged current reaction on free protons, and the ν_x component through neutral current reactions. For each of these components one should determine, ideally, not only the total rate, proportional to $L_\nu / \langle E_\nu \rangle \int \sigma(E_\nu) f(E_\nu) dE_\nu$, ($f(E_\nu)$ is the normalized energy distribution; typically assumed to be the Fermi-Dirac thermal one) but also the temperature, or equivalently $\langle E_\nu \rangle$. If, and only if this program can be accomplished, can one reach reliable conclusions about supernova astrophysics and/or neutrino oscillations.

2 Detecting $\bar{\nu}_e$ and ν_e through charged current reactions

It is relatively easy to detect $\bar{\nu}_e$, since most detectors contain free protons and one can utilize the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ with large cross section and a characteristic signature of the time and position correlated positron and neutron.

The cross section is well known. Neglecting the small neutron recoil energy ($\sim E_\nu^2/M_p$), one can simply relate the positron energy to the incoming neutrino energy,

$$E_e^{(0)} = E_\nu - \Delta, \quad \Delta = M_n - M_p = 1.293 \text{ MeV} \ . \tag{8}$$

The differential cross section to this ($M_p \to \infty$) order is

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{dcos}\theta}\right)^{(0)} = \frac{\sigma_0}{2}\left[(f^2+3g^2)+(f^2-g^2)v_e^{(0)}\cos\theta\right]E_e^{(0)}p_e^{(0)}\ ,\ \sigma_0 = \frac{G_F^2\cos^2\theta_C}{\pi}(1+\Delta_{inner}^R) \tag{9}$$

where the vector and axial-vector coupling constants are $f = 1$, $g = 1.26$ and $\Delta_{inner}^R \simeq 0.024$ represents the inner radiative corrections. Integrating over angles one obtains the standard result for the total cross section, which can be also related to the neutron lifetime τ_n,

$$\sigma_{tot}^{(0)} = \sigma_0\ (f^2+3g^2)\ E_e^{(0)}p_e^{(0)} = 0.0952\left(\frac{E_e^{(0)}p_e^{(0)}}{1\ \mathrm{MeV}^2}\right)\times 10^{-42}\ \mathrm{cm}^2 = \frac{2\pi^2/m_e^5}{f_{p.s.}^R\tau_n}\ E_e^{(0)}p_e^{(0)}\ , \tag{10}$$

where $f_{p.s.}^R = 1.7152$ is the phase space factor, including the Coulomb, weak magnetism, recoil, and outer radiative corrections. For supernova $\bar{\nu}_e$ terms of order $1/M_p$ should be included. The expressions for the cross section to that order, including angular distribution, can be found in Ref. [13].

For the 'standard' SN with $T_{\bar{\nu}_e} = 5$ MeV one expects $\sim$8300 e^+ events in Superkamiokande, and $\sim$360 events in the light water part of SNO. SNO will be able to detect $\bar{\nu}_e$ also by the charged current reaction on deuterons; one expects about $\sim$80 events of this kind with two neutrons in the final state. In KamLAND, which is a scintillation detector, the correlation between the positron and the neutron capture γ-rays can be used; one expects $\sim$330 events there. Altogether, it should be possible to measure with good accuracy the luminosity and energy distribution of supernova $\bar{\nu}_e$. In Superkamiokande the statistics ought to be sufficient to determine also the time dependence of the $\bar{\nu}_e$ luminosity and temperature.

It is more difficult to detect ν_e since they interact only with neutrons and are expected to have lower temperature ($T_{\nu_e} = 3.5$ MeV). Both ^{16}O (in water Čerenkov detectors) and ^{12}C (in scintillation detectors) have high thresholds for the ν_e induced charged current reactions, 15.42 MeV and 17.34 MeV, respectively. Thus, one expects negligible yields for the charged current reactions on these targets as long as T_{ν_e} is indeed only 3.5 MeV.

In SNO the 'solar' reaction $\nu_e + d \to e^- + p + p$ with mere 1.44 MeV threshold should yield about 80 events, perhaps sufficient to determine, at least crudely, the temperature T_{ν_e} and the corresponding luminosity.

Since cross sections for the charged current ν_e interaction with nuclei typically increase quickly with E_ν, the count rates would increase dramatically if $\nu_e \leftrightarrow \nu_x$ mixing occurs, which is likely to happen. Hence observation of the ν_e signal represents a sensitive test for oscillations. In KamLAND one expects only $\sim$2 events for the $\nu_e{}^{12}\mathrm{C} \to {}^{12}\mathrm{N}_{gs}e^-$ reaction if $T_{\nu_e} = 3.5$ MeV. That rate increases to $\sim$ 15 for vacuum oscillations, and to 27 for the resonant MSW oscillations. (This reaction has an excellent signature since one can use the delayed coincidence with the ^{12}N β^+ decay.) In SuperKamiokande the reaction $\nu_e\ {}^{16}\mathrm{O} \to {}^{16}\mathrm{F}^*e^-$ results in only $\sim$ 20 events for $T_{\nu_e} = 3.5$ MeV. However, if through oscillations the effective $T_{\nu_e} = 8$ MeV, the yield increases dramatically to $\sim$860 events [14, 15]. The electrons from the ν_e charged current reaction on ^{16}O can be distinguished, in principle, from the positrons from $\bar{\nu}_e$ on protons by their angular distribution.

Lead has been proposed as the target material in OMNIS and LAND supernova neutrino detectors. The charged current reaction on ^{208}Pb induced by ν_e has threshold of only 2.9 MeV, but the corresponding strength is dominated by the excitation of the giant Gamow-Teller resonance at about 16 MeV excitation energy. The proposed detectors would register neutrons emitted by the decay of the final ^{208}Bi for the charged current reaction or ^{208}Pb* for the neutral current reaction. Generally, it would be difficult to separate the charged and neutral current responses with such scheme. (Although with the 'normal' hierarchy, Eqs. (4,5), the neutral current signal would dominate.) However, in Ref. [16] it was shown that the observation of the double neutrons could serve as a signature of the charged current induced events in the case of oscillations. One drawback is that the corresponding cross sections for both reactions are rather uncertain. In fact, the two recent calculations of these quantities [16, 17] differ by about a factor of two. Thus, if the lead based supernova detectors are ever build, experimental determination of these cross sections will be necessary.

3 Detecting ν_x neutrinos through neutral current scattering

The supernova ν_x, i.e. ν_μ and ν_τ with their antiparticles, do not have enough energy to induce charged current (CC) interactions. Thus, they can be detected only through their neutral current (NC) scattering. In order to detect the NC scattering one has to find, first of all, the appropriate signature, i.e. a reaction that can be clearly recognized and separated from the CC channels. Since NC scattering is flavor blind, the contribution of the ν_e and $\bar{\nu}_e$ scattering has to be subtracted in order to isolate the ν_x effect. This condition more or less eliminates neutrino-electron scattering, where the ν_e and $\bar{\nu}_e$ contribution dominates. However, in semileptonic NC scattering the cross section typically increases fast with energy, and hence the ν_x contribution will dominate the NC yield. (The fact that there are four flavors in the ν_x flux helps as well.)

The other difficulty is that in a typical NC reaction there is no spectral information; only the number of events per unit time can be measured. Generally, the scattering rate (per s) is:

$$\frac{dN_{NC}}{dt} = C \int dE\, f(E) \left[\frac{\sigma(E)}{10^{-42}\mathrm{cm}^2}\right] \left[\frac{L(t-\Delta t(E))}{E_B/6}\right] , \qquad (11)$$

where for SuperKamiokande

$$C = 9.21 \left[\frac{E_B}{10^{53}\ \mathrm{ergs}}\right] \left[\frac{1\ \mathrm{MeV}}{T}\right] \left[\frac{10\ \mathrm{kpc}}{D}\right]^2 \left[\frac{\mathrm{det.\ mass}}{1\ \mathrm{kton}}\right] n\, , \qquad (12)$$

T is the spectrum temperature (where we assume $\langle E \rangle = 3.15T$, as appropriate for a Fermi-Dirac spectrum), $f(E)$, the neutrino energy distribution is in MeV^{-1}, and n is the number of target nuclei per water molecule. Also, $\Delta t(E)$ is the possible delay caused by the finite neutrino mass.

Thus, NC scattering rate depends on both the luminosity and temperature, and their effects cannot be directly separated. On the other hand, the NC signal is obviously independent of possible oscillations between active (as opposed to sterile) neutrinos.

There are several ways in which the NC signal in existing detectors can be determined. In water Čerenkov detectors, one can use the signal proposed in [18] according to which the ν_x neutrinos will excite ^{16}O into the continuum that will deexite dominantly by the emission of either proton or neutron. There is a sizable probability (about 30%) that the resulting ^{15}N or ^{15}O nucleus will be in a bound excited state, as indicated in Fig. 1. These states, in turn, deexite by γ emission with characteristic energies between 5 and 10 MeV, above the SuperKamiokande threshold, and easily separated from the background positrons from $\bar{\nu}_e p \to e^+ n$. In SuperKamiokande one expects about 700 events of this kind.

In SNO the obvious NC signal is the deuteron disintegration, $\nu_x + d \to n + p + \nu_x$. It can be recognized by detecting a single neutron, but no electron (or positron). The rate is obtained by the same equations as above, except in Eq. (12) one should replace $9.21 \to 8.28$. There will about 400 NC ν_x induced events in SNO, with another ~ 85 induced by ν_e and $\bar{\nu}_e$.

In scintillation detectors, such as KamLAND or Borexino, ν_x NC scattering with excitation of the 15.11 MeV $T = 1, I^\pi = 1^+$ state in ^{12}C is possible (see Fig. 2). This process offers a very distinct signature and has the further advantage that the corresponding cross section is calculable accurately, and has been verified by the KARMEN and LSND experiments. One expects ~ 60 events with 15.11 MeV γ in KamLAND.

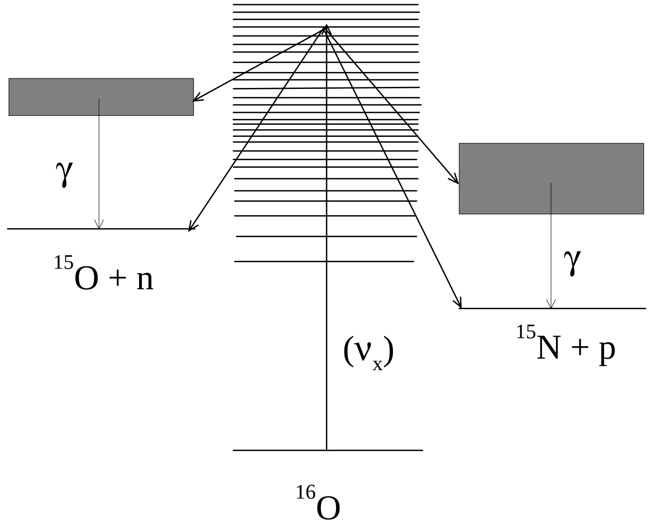

Figure 1: Schematic illustration of the detection scheme for supernova ν_x neutrinos in water Čerenkov detectors.

Finally, as mentioned above, in lead based detectors the single neutron events will be dominated by the NC ν_x scattering.

Thus, there will be a rather accurate information on the rate of the NC events. By combining the data from different detectors, one can try to determine the ν_x luminosity and temperature separately. This should be possible, at least crudely, since the mentioned reactions, while all proportional to the ν_x luminosity, will have slightly different dependence on neutrino energy in the various respective cross sections.

4 Neutrino elastic scattering on protons

Ideally, one would like to use NC scattering combined with some spectrum information, not just rate as in the previous section. As stressed previously also, the seemingly obvious candidate process, neutrino - electron scattering, will be dominated by the ν_e and $\bar{\nu}_e$ scattering, and thus is not very convenient to study the ν_x scattering.

In detectors with low detection threshold, such as the scintillator based KamLAND and Borexino, one can, in principle use for this purpose the elastic scattering on protons [1]. The corresponding differential cross section is

$$\frac{\mathrm{d}\sigma}{\mathrm{d}T_p} = \frac{G_F^2 M_p}{\pi}\left[(c_A^2 + c_V^2) - (c_A^2 - c_V^2)\frac{T_p M_p}{2E_\nu^2} - (c_V \mp c_A)^2 \frac{T_p}{E_\nu} \pm 2 c_M c_A \frac{T_p}{E_\nu}\right] , \tag{13}$$

where $c_V = 1/2 - 2\sin^2\theta_W = 0.0375$, $c_A = 1.26/2$, $c_M \simeq -\mu_n/2$, and $\pm$ refers to ν and $\bar{\nu}$, respectively. (We have neglected the possible effect of the strangeness component of the proton). The total cross section is proportional to E_ν^2, so the signal will be dominated by ν_x, particularly above reasonable detection thresholds. However, while the recoiling protons scintillate, the scintillation light is quenched, compared to electrons or γ. Thus, the relevant observable energies are ≤ 1 MeV, and difficult to detect and separate from backgrounds. However, in a sensitive low background detector one might be able not only to count the number of events, but actually observe the proton recoil spectrum. The cross

[1] The content of this section is based on the suggestion of John Beacom, for details see [19].

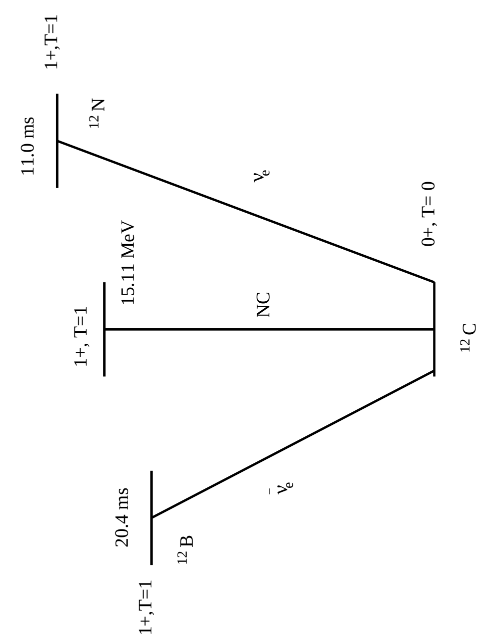

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Figure 2: Illustration of the excitation of the $T = 1,\ I = 1^+$ triad in mass $A = 12$ nuclei .

section, without account of quenching, and for the Fermi-Dirac spectrum of incoming neutrinos, is shown in Fig. 3. Note the sharp dependence on the neutrino temperatures.

Let us assume that one will be able to extract from measurement some spectral information on the recoiling protons. Would that make it possible to distinguish the cases in which the ν_x luminosity and temperature conspire in such a way that they lead to the same total number of events, and therefore are indistinguishable based only on Eq. (11)? The answer is yes, and how this could be accomplished is illustrated in Fig. 4. One can see that the proton recoil spectra sensitively depend on the neutrino temperature, with the ratio of the low and high energy yields decreasing with the increasing temperature. In a detailed simulation [19] the power of such discrimination was demonstrated by taking into account the statistical fluctuation of the expected data. As shown in Fig. 5 one expects about 10% resolution on both the ν_x temperature and total energy carried by these neutrinos.

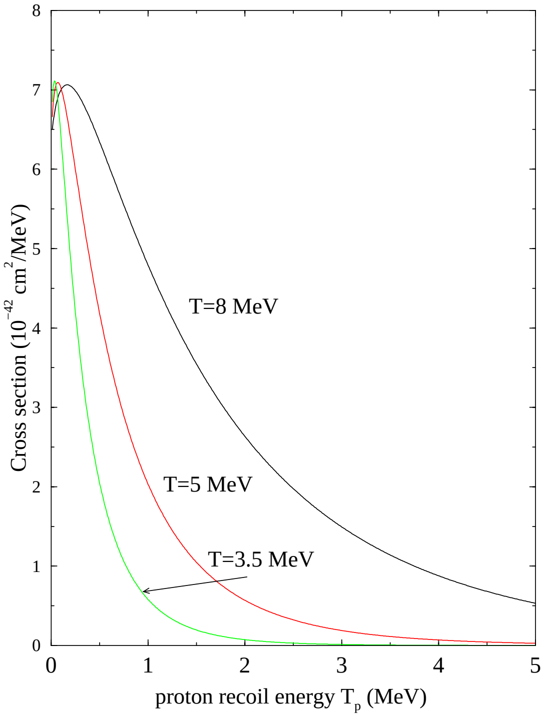

Figure 3: Cross section of the elastic neutrino scattering on protons for the indicated temperatures of the incoming neutrinos. Proton recoil energies without quenching are used.

It should be stressed once more that the considered NC signal is independent of neutrino oscillations into 'active' flavors, i.e. $\nu_e \leftrightarrow \nu_{\mu,\tau}$ and obviously $\nu_\mu \leftrightarrow \nu_\tau$. If this signal can be in fact detected, it would measure the luminosity and temperature of the hottest component of the supernova neutrino emission spectrum.

5 Conclusions

In this lecture I have shown how, through the combination of the existing (or soon to be operational) detectors, one can determine simultaneously and independently the luminosities and average energies (or temperatures) of the three expected components, ν_e, $\bar{\nu}_e$ and ν_x, of the next Galactic supernova neutrino flux. For a 'standard' supernova near the center of our galaxy, at 10 kpc, I have estimated the corresponding count rates, neglecting for a moment the possible effects of neutrino oscillations.

Having this set of quantities will make it possible to verify, or find deviations, from the basic assumptions about the supernova neutrino emission: the equal luminosity in each of the six neutrino flavors, and the hierarchy of decoupling temperatures. Also, one should be able to determine the total emitted energy, essentially the supernova binding energy, and the total neutrino fluence. Such observables will, in turn, severely constrain theoretical models of supernova neutrino emission, and allow one to deduce conclusions about the possible role of neutrino oscillations.

Most of the original results reported here were obtained in a highly pleasurable collaboration with John Beacom. The work was supported by the US DOE contract DE-FG03-88ER40397.

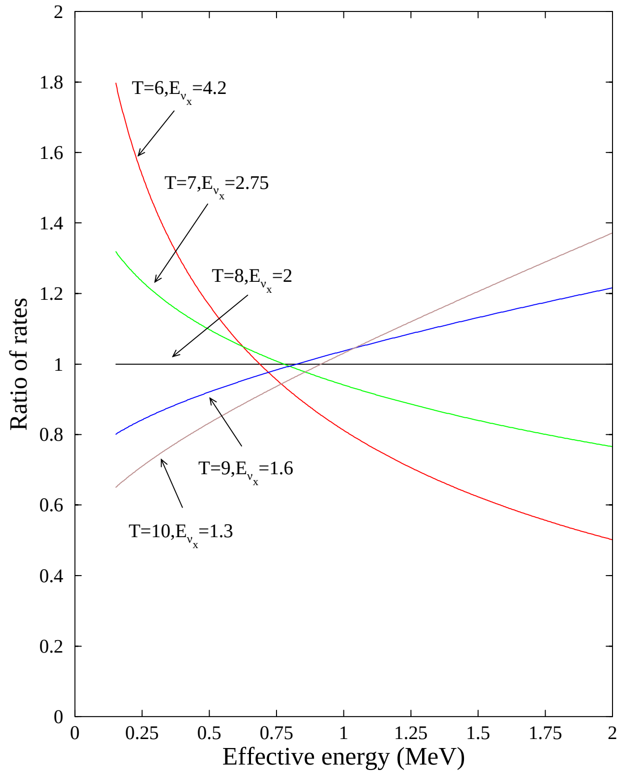

Figure 4: Ratio of proton yields, as a function of the effective quenched energy, to the standard case of $T = 8$ Mev, and the total energy emitted in ν_x equal to 2×10^{53} erg. All considered cases result in the same total number of events above the threshold of 200 keV of the effective energy.

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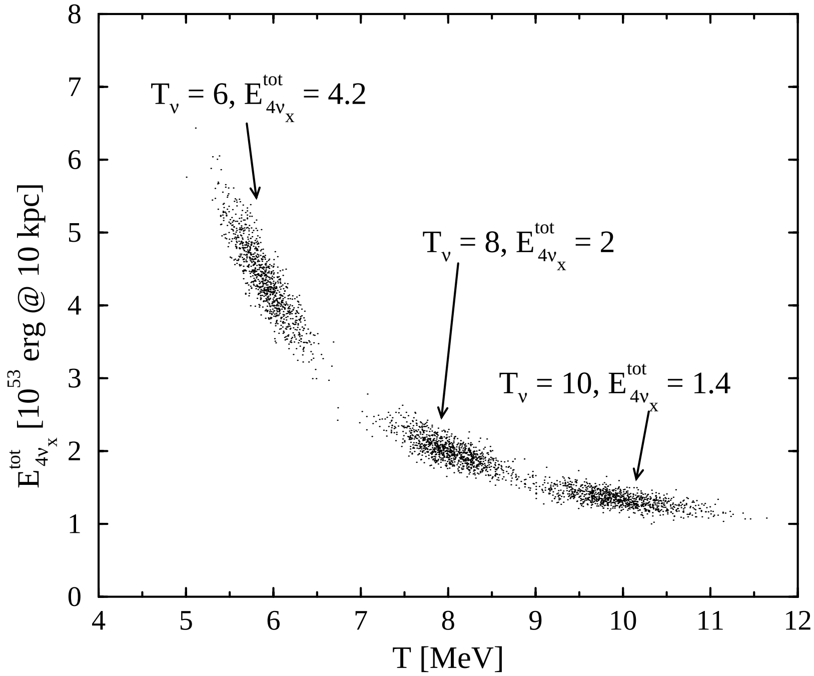

Figure 5: Monte Carlo simulation of the combined fit to T_{ν_x} and the total energy carried by such neutrinos, $E^{tot}_{4\nu_x}$.

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